MECHANICAL PROPERTIES OF CORONARY ARTERIES AND INTERNAL MAMMARY ARTERIES BEYOND PHYSIOLOGICAL DEFORMATIONS

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Abstract- **Passive circumferential and axial mechanical properties of porcine coronary arteries and internal mammary arteries (IMA) were measured and compared. The cylindrical specimens were subjected to axial stretch and internal pressures up to 300 mmHg. Stress-strain relations of the arteries were calculated from the measured data and compared. It was found that the stresses in the IMA were much higher and that the IMA is stiffer than the coronary artery, especially in the circumferential direction. The axial stress in the coronary artery increased substantially after axial stretching, this in contrast to the axial stress in the IMA.**
Keywords- **coronary artery, internal mammary artery, stress, strain, bypass**

I. INTRODUCTION

Coronary artery bypass surgery is changing recently. Surgery on the beating heart with local mechanical stabilizers is practiced in 15-20 % of the cases worldwide. Tele-manipulation systems are introduced that allow surgeons to explore minimally invasive coronary surgery [1]. These developments will require new techniques for coronary artery bypass grafting because of limited access and space. Many patents of facilitated anastomotic techniques show the use of anvils and other microstructures [2]. Applying such techniques often causes extreme deformations in the arterial wall of both donor and recipient vessel and this could lead to severe damage of arterial wall structures. These extreme deformations can initiate intimal hyperplasia, which could eventually lead to stenosis of the anastomosis. Therefore it is important to know more about the mechanical properties of arteries involved in coronary artery bypass surgery. We investigated the main coronary arteries and a graft, the IMA, because of its good clinical results [3].

II. METHODOLOGY

For this study the vessels of 13 healthy Landrace pigs (weight 70-90 kg) were used. The animals were sacrificed in the course of other experiments. A total of 8 cylindrical segments of coronary arteries and 6 segments of the IMA were harvested. All arteries were measured within 24 hours after termination. The coronary arteries were removed from the hearts, all side branches were carefully closed with small clips. Surrounding tissue and loose adventitial fibers were removed. The mechanical properties were measured by subjecting the arterial segments to inflation and axial tension in an experimental setup. Both ends of each arterial segment were connected to metallic cannulae with sutures. The cannulae were connected to a tensile testing machine with which both the axial lengthening of the segment could be regulated and the axial force was measured. In general, a segment of a vessel shortens after removal from the surrounding tissue. To approximate their original length, the arteries were given pre-stretches in the axial direction. The upper cannula was closed and the lower cannula was connected to a reservoir with Tyrode solution (in mM: NaCl 140; KCl 4.9; $MgSO_4$ 1.2; NaH_2PO_4 1.8 and Hepes 5). The cannulated segment was placed in a small chamber with parallel glass walls, which was filled with the same Tyrode solution at a constant temperature of 37 ^{0}C. A dual beam laser-micrometer was placed around the glass chamber with two beams pointing at the middle section of the arterial segment at an angle of 90^0. The laser device measured the external diameter of the artery during inflation with both beams simultaneously and calculated the average diameter, correcting for oval shaped segments. The inflation of the artery with Tyrode solution was pressure regulated within a range of 0-300 mmHg. The pressure was elevated from 0-100 mmHg with incremental steps of 10 mmHg and from 100-300 mmHg with incremental steps of 20 mmHg. To establish a more constant mechanical response, the arteries were preconditioned before the experiment by elevating the pressure to 200 mmHg for 5 times.

Before the experiment, the length L of the unloaded vessel was measured with a caliper. After the tests, a ring segment was taken out of each artery at the spot where the diameter was measured by the laser. By taking digital pictures from the microscopic images of these rings, the unloaded external diameter D, mid-wall radius R and wall thickness H could be measured with a computer. At several axial lengths l, the external diameter d and axial force f were measured as a function of rising pressure p. Assuming arterial wall incompressibility, the current mid-wall radius r and the wall thickness h could be computed. The collected data were used to calculate the Green-Langrange strains (E_θ, E_z) and the second Piola-Kirchhoff stresses (S_θ, S_z) in the circumferential (θ) and axial (z) directions.

The strains are given by,

$$E_\theta = \frac{1}{2}\left(\lambda_\theta^2 - 1\right), \qquad E_z = \frac{1}{2}\left(\lambda_z^2 - 1\right) \tag{1}$$

with λ_θ =r/R and λ_z =l/L being the principal stretch ratios in the circumferential and axial directions for the middle surface of the vessel wall.

The stresses are

$$S_\theta = \frac{\sigma_\theta}{\lambda_\theta^2}, \qquad S_z = \frac{\sigma_z}{\lambda_z^2} \tag{2}$$

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Abstract

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with σ_θ and σ_z the true stresses in the circumferential and axial directions,

$$\sigma_\theta = p\left(\frac{r}{h} - \frac{1}{2}\right), \qquad \sigma_z = \frac{\sigma_\theta}{2} + \frac{f}{2\pi r h} \qquad (3)$$

III. RESULTS

The average initial external diameter of the coronary arteries was 3.39 ± 0.38 mm and the average initial wall thickness 0.71 ± 0.16 mm, for the IMA these dimensions were respectively 3.39 ± 0.46 mm and 0.35 ± 0.07 mm. Because of the corresponding external diameter these vessels make a good fit in a bypass procedure. Fig. 1 shows the areas in which the circumferential stress-strain relations of all the measured specimens were situated for an axial stretch of λ_z=1.3. The axial stress versus the circumferential strain relation for all specimens at the same stretch λ_z=1.3, is given in fig. 2. For both arteries, increasing the axial segment length with 30 % approximated the *in vivo* length. The non-linearity of the stress-strain relationships is obvious. The strongest increase of the stress started at pressures of approximately 100 mmHg. The results show that the stresses in the IMA were much higher than in the coronary artery, especially in the circumferential direction. The slopes of the curves, which are an indication for the stiffness of the material, show that the IMA is stiffer than the coronary artery. Notice the difference of the shape of the curves for both types of arteries. The elastic IMA shows a "S"-shaped stress-strain relation in the circumferential direction, which is not the case for the muscular coronary artery. Fig. 3 shows the typical stress-strain relationship in circumferential direction of one coronary artery at increasing values of axial stretch. With increasing axial length, the circumferential wall stress tends to rise slightly. In fig. 4 the axial stress is displayed in relation to the circumferential strain for the same coronary artery. The axial stress shows a much stronger increase as a result of the axial stretching. Fig. 5 displays the circumferential stress as a function of the circumferential strain for an IMA. Higher axial stretching has not much effect on the circumferential stress level. In contrast to the coronary artery,
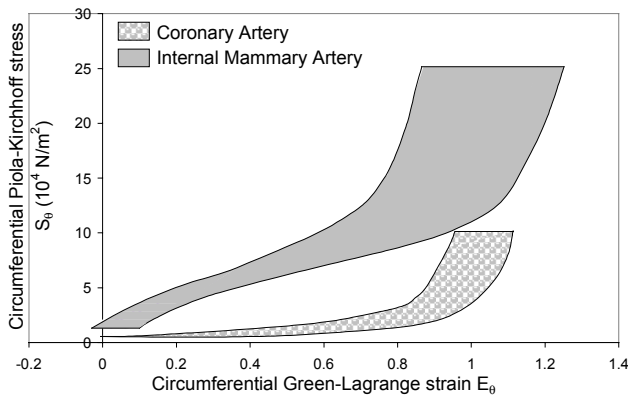
the axial stress in the IMA, as depicted in fig. 6, is hardly rising at higher levels of axial stretch.

IV. DISCUSSION

The coronary artery and the IMA are anatomically different blood vessels. The coronary artery is an artery of the muscular type, which means that the media consists mainly of smooth muscle cells. The IMA is an elastic artery, the media contains many elastic fibers. The mechanical characteristics of these vessels are determined by its components and the structural interrelationship between the components. Although the IMA is classified as an elastic artery, the stress-strain results in the pig show that it is actually stiffer than the coronary artery. It should be taken into consideration though, that these experiments were performed on healthy arteries. Bypass surgery is performed on patients with atherosclerotic coronary arteries, which may be substantially stiffer than the healthy porcine coronary arteries.

V. CONCLUSIONS

The experiments showed that the circumferential and axial mechanical properties of the porcine coronary arteries and the IMA's are different. The IMA is much stiffer than the coronary artery, especially in the circumferential direction of the vessel wall in the lower pressure range. In the higher pressure range, the circumferential stress level in the IMA is much higher than in the coronary artery. Axial stretching has the largest effect on the axial stress in the coronary arteries. The results of these experiments will be used for simulations. By means of finite element analysis, situations of extreme deformation of these arteries can be modeled. Further investigations are necessary to determine whether the arterial wall is actually permanently damaged by such high wall stresses.

Fig. 1. Areas in which the circumferential stress-strain relations exist for all measured arteries at axial pre-stretch λ_z=1.3.
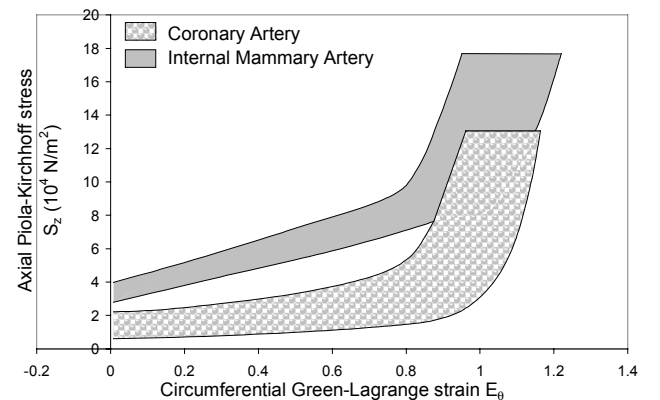

Fig. 2. Areas in which the axial stress versus circumferential strain relations exist for all measured arteries at axial pre-stretch λ_z=1.3.
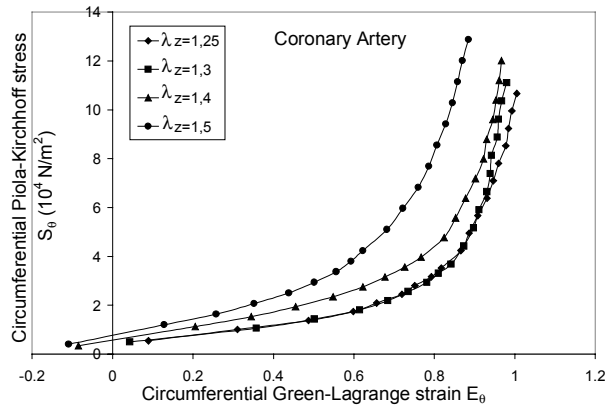
Fig. 3. Circumferential stress versus circumferential strain for a coronary artery at different axial stretches (Markers indicate the pressure steps).
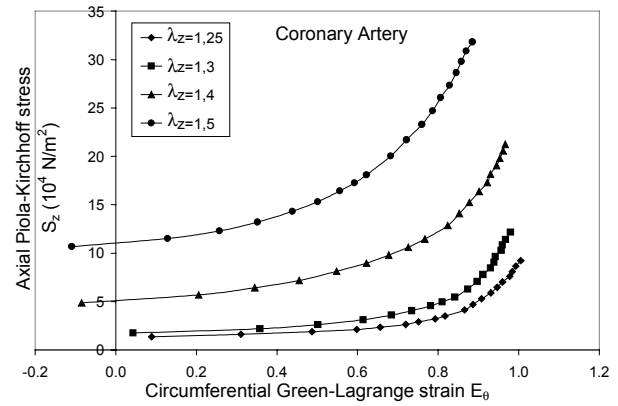

Fig. 4. Axial stress versus circumferential strain for a coronary artery at different axial stretches.
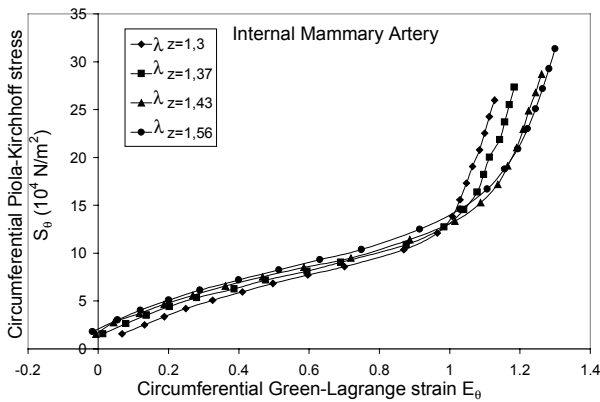

Fig. 5. Circumferential stress versus circumferential strain for an internal mammary artery at different axial stretches.
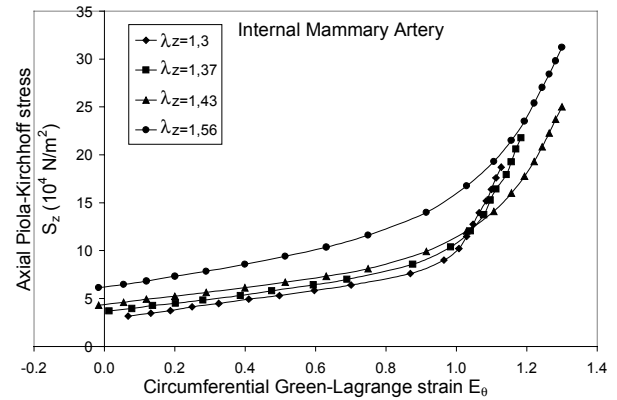

Fig. 6. Axial stress versus circumferential strain for an internal mammary artery at different axial stretches.

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